"OFF-THE-SHELF" ANTIFREEZE CONCRETE: A DEMONSTRATED TECHNOLOGY

Lynette Barna
USAERDC-CRREL
Lynette.A.Barna@erdc.usace.army.mil

Charles Korhonen, Ph.D., P.E.
USAERDC-CRREL
Charles.J.Korhonen@erdc.usace.army.mil

Peter Semen
USAERDC-CRREL
Peter.M.Semen@erdc.usace.army.mil

INTRODUCTION

Concrete construction operations are affected by cold weather. At low temperatures, normal concrete requires more time to set, finish, and gain strength. Should the internal temperature of freshly placed portland cement concrete fall below +5°C, cold weather concrete procedures must be initiated to protect against freezing. Conventional practice necessitates constructing heated enclosures to maintain a sufficient curing temperature. Freshly emplaced concrete may be severely damaged by the 9% increase in volume of water freezing into ice. The Engineer Research and Development Center, Cold Regions Research & Engineering Laboratory (USAERDC-CRREL) recently completed a three-year study that demonstrated the feasibility of using commercially available, or 'off-the-shelf', chemical admixtures to depress the freezing point of water in concrete down to an internal concrete temperature of –5°C. The results of the study are available in Korhonen et al (2004). Extensive laboratory testing was conducted that produced eight practical antifreeze concrete formulations. Four field trials in New Hampshire and Wisconsin during the winters of 2002 and 2003 validated this approach. A demonstration project, conducted in Concord, New Hampshire in February 2003, successfully transferred this technology to one of the study's participating agencies.

A significant limitation to conventional cold weather concreting is the additional cost associated with building and heating temporary enclosures. The structures are often cramped and restricted. The costs for heating the enclosure for periods before and after concrete placement can be significant; and maintaining a uniform temperature within the structure is often difficult (Fig. 1). Antifreeze concrete offers a solution to these limitations as the concrete may be placed directly on an ice-free substrate. Upon finishing, the surface is covered with a sheet of plastic to retain moisture. The antifreeze approach allows concrete operations to continue longer, thereby extending the concrete construction and repair season. It is estimated the season may be extended by as much as 60 days in the northern tier states of the continental U.S. (Fig 2).

DEVELOPING 'OFF-THE-SHELF' FORMULATIONS

The purpose of the study was to develop and test concrete formulations containing commercially available chemical admixtures capable of protecting freshly emplaced concrete from freezing down to an internal concrete temperature of –5°C. Appreciable strength gain can occur at that temperature, even when the ambient air temperature may be much colder. Techniques needed to batch, mix, and transport antifreeze concrete were developed and tested under both lab and field conditions. To be certain that the concrete delivered to a jobsite met the desired freezing point depression, and to monitor the in-place strength gain of the concrete after placement, quality control and assurance methods were developed and refined.

Chemical admixtures are widely used today to enhance concrete performance. However, no single admixture, when used within the manufacturer's recommended dosage levels, is capable of protecting concrete from freezing down to –5°C. In this study, currently available chemical admixtures were used in combination to depress the freezing point of the mix water and accelerate the hydration of portland cement. Admixtures from two major manufacturers were evaluated that have either met the testing requirements as specified by ASTM C 494 or ASTM C 260, or are considered acceptable for use by the industry. This allows antifreeze formulations to be adopted directly into practice without the need for additional standardized testing. Dosage levels for all of the admixtures were within the manufacturers recommendations. It is recommended that agencies conduct testing on their own as a way to become familiar with antifreeze mixes.

Listed in Table 1 are the general types of admixtures evaluated in this study. Water reducers maintain workability while reducing the water-cement ratio. Accelerators increased the set time and aided in early strength gain. Retarding admixtures reduced the early stiffening from the accelerators. Corrosion inhibitors and shrinkage reducers provided added freezing point depression. Table 2 shows a sample of an antifreeze mixture. It should be noted that not all admixtures had to be used in any one given concrete.

Antifreeze concrete must meet three performance requirements: 1) depress the freezing point of the mix water to prevent ice formation; 2) provide water to aid the hydration of cement and, 3) permit strength gain at a low curing temperature. To assist in the usability of antifreeze mixes, the concrete had to be workable, capable of entraining air, and meet the design temperature of –5°C. In the lab, numerous trial mixes were tested to determine the appropriate combinations and dosage levels of admixtures that met our initial criteria for workability, air content, and initial freezing point of freshly mixed concrete. Eight final candidate mixes met these initial criteria and performed well at low-temperatures. Four of the final antifreeze mixes used the admixtures from the first manufacturer's product line (referred to as Mixes 1-4), and the remaining four mixes used admixtures from the second manufacturer (Mixes A-D). Based on these results from the lab, these mixes were candidates for field validation.

LABORATORY INVESTIGATION

The process of selecting combinations of admixtures and the proper dosing levels was narrowed down by how well the mix met our three initial screening tests of: workability, air entrainment, and initial freezing point. To the construction team mixing, placing, and finishing the concrete, an antifreeze mix should appear and behave similar to a normal concrete mix placed at a warmer temperature. Strength testing was also conducted on candidate mixes that met the initial screening criteria.

A standard control concrete mix, used throughout the lab study, provided the foundation on which all of the antifreeze mixes were formulated. It was also used to compare the performance of the antifreeze mixes. According to ACI recommended practice 211.1, the control mix used in this study is characteristic of a winter concrete mix used for transportation projects. The coarse aggregate size was 19 mm, the target slump was 100 mm, and the target water-cement ratio was 0.45 (with a maximum of 0.50). The acceptable air content was 6.0%, ±1.5%.

Throughout the study, the cement and aggregates were locally available and used for consistency. The cement was a Type I/II, based on ASTM C 150, and manufactured by Lafarge North America, St. Constant, Quebec. As specified in the control mix, the fine aggregate was a natural sand; and the coarse aggregate was 19 mm crushed ledge stone. Both of these aggregate materials met ASTM C 33 requirements. Water used in the mixes was regular tap water equilibrated to an ambient temperature of approximately 23°C. All mixing in the lab was performed using a 0.04 m^3 rotary drum mixer.

Workability

In normal concrete, a low slump may be remedied by adding more water. In contrast, antifreeze mixes contain high doses of accelerators, causing them to lose slump more quickly. Adding more water to an antifreeze mix will reduce the concrete's ability to resist freezing. This becomes a critical issue when considering the transit time from the ready mix plant to the jobsite and handling any construction delays. The antifreeze mixes must be capable of transportation times up to 45 minutes and provide an additional 20 to 30 minutes of working time for emplacement and finishing. This was tested in the lab by taking slump measurements over time for each mix, as compared to the control (Fig 3). Three dosing schemes emerged: 1) dosing all admixtures at the plant; 2) dosing part of the admixtures at the plant and the remainder at the site; and 3) dosing all admixtures at the site.

The first method, dosing all of the admixtures at the plant, is most advantageous when there are no further admixtures to be added to the mix and a relatively short haul time is required. Slump loss is expected during transport to the jobsite. Therefore, the initial slump must be high enough upon leaving the plant to eventually fall within range once at the jobsite. There is also the greatest potential for a reduction in the air content with this method, although this may be remedied once at the site. This method leaves little room for any necessary corrective action that may be taken at the site should there be any delays.

In the second dosing method, some of the admixtures are dosed at the plant and the rest are added at the jobsite. At the plant, admixtures that have less of an effect on the mix may be dosed with little impact during transport. The remaining admixtures, that have a larger impact on the mix, are dosed at the site. This provides more flexibility at the jobsite to guard against construction delays. A disadvantage of this method is that it requires transporting admixtures to the site well in advance of the arrival of the truck. In some instances, the admixtures administered at the jobsite may increase the slump well beyond the target. Then it becomes necessary to wait until the slump drops before releasing the concrete into the forms.

The third method is to dose all of the admixtures at the jobsite. This method, in essence "zero delivery time," offers the most flexibility and minimizes the effects of rapid slump loss since all of the admixtures are dosed into the mix when they are needed, and the concrete may then be released into the forms. While this method requires additional preparation for adding admixtures, it maximizes the operational window by adding the admixtures when ready for them, particularly when construction delays occur. When using this method, care must be taken that the concrete does not freeze while in transit.

Air Content

The concrete mix must be capable of entraining air to resist damage due to freeze-thaw environments. A target air content of 6.0% (±1.5%) was set for both the control and antifreeze mixes. Measurements were taken 5 minutes after the concrete was completely mixed and again 50 minutes later to see the effects of air content over time. To simulate dosing a mix entirely at the jobsite (method 3 above), an air content measurement was taken once the last admixture was added and thoroughly mixed. All air content measurements followed the volumetric method, ASTM C 173. The results of the air measurements for the control and antifreeze mixes are given in Table 3.

The 5-minute air content measurements from all of the mixes from the first set of commercial admixtures (Mixes 1-4) were within an acceptable range. All of these mixes used the second dosing scheme, where some of the admixtures were added at the plant, and the remainder at the jobsite. At the second reading 50 minutes later, all air content measurements exceeded the target value. For the second set of commercial admixtures, Mixes A and B met the target range. The air content in Mix C, at 2.0%, was lower than the target, while the estimated air content for Mix D was quite high at approximately 11%. At the 55-minute mark, air content values for Mixes A, B, and D met the target air content value, while Mix C increased by less than 1 percent. Mixes A and D used the second dosing method, and Mixes B and C used the first dosing method. The purpose of this was to assure that air entrainment was possible with the antifreeze mixes. Even though air content values vary, and may be well above the target of 6.0%, the antifreeze mixes do not impede air entrainment.

Initial Freezing Point

A freezing point measurement is used to ensure that the fresh concrete meets the –5°C freezing temperature. In the lab, cylinders of fresh concrete (23°C) are placed in a –20°C cold room and allowed to completely freeze. During casting, a thermocouple is placed at the center of mass of the concrete cylinder and connected to a datalogger that records the temperature. The curve in Figure 4 illustrates a typical freezing point measurement. The sample cools and loses its heat until ice begins to form. The freezing point temperature is the point on the curve where the slope flattens (Korhonen et al., in preparation). At this point, water in the mix is supercooled, meaning that its temperature is colder than that required for ice to melt. When ice crystals form, there is a slight increase in the temperature (a matter of tenths of a degree) caused by the release of the latent heat of fusion. The water in an antifreeze concrete mix does not freeze at one temperature because of the solution of admixtures in the water. As pure ice forms, the chemical concentration increases, requiring colder temperatures to freeze.

A relationship exists between the amount of water in the mix and the resulting freezing point. An increase in the amount of water in the mix results in a higher freezing point temperature. An example of both the freezing point measurement and the total percent solids are shown in Table 2. In an antifreeze mix, all of the water must be accounted for. The amount of water associated with the admixtures must be determined and then the total amount of mix water is adjusted. This is based on the calculated percent solids content of the mix.

Compressive Strength

Compressive strength testing was conducted to confirm that the antifreeze mixes gained strength at low temperatures. Sets of compression cylinders 76x152 mm were cast, capped to retain moisture, and placed on wire racks to cure in air at 23, +5, and –4°C. For the cold temperatures, the cylinders were cured in large cold rooms. A curing environment of –4°C was selected because it is a very harsh curing condition, and it was close to the design temperature of –5°C to be certain that the cylinders did not freeze. Prior to strength testing, cylinders cured at –4°C were brought out to room temperature and warmed to +5°C. Compressive tests were performed at 1 (control and

Company A, only), 3 (Company B only), 7, 14, and 28 days. Figures 5 and 6 show the strength gain of all eight antifreeze mixes cured at –4°C as a percentage of the 28-day strength of the control concrete cured at 25°C. For a mix containing Type I cement cured at 4.4°C, ACI 306-R88 (1988) has established guidance for acceptable rates of strength-gain. This was the baseline to compare the performance of our antifreeze mixes. While initially slow to gain strength, the cylinders cured at –4°C outperformed the +5°C control concrete. The only exception to this was Mix 2, a mix that contained a reduced amount of accelerators.

A recovery test to observe any harmful effects of the admixtures on long-term strength gain was conducted using a set of cylinders from each mix at the three curing temperatures. After 28 days, the cylinders were removed from their curing environments and returned to room temperature to continue curing for an additional 28 days (Figures 5 and 6). The 56-day strengths of the antifreeze concrete, including Mix 2 (Fig 5), exceeded the 25°C control mix, or 100%, illustrating that the admixtures in the antifreeze mixes do not harm the long-term strength gain.

QUALITY CONTROL AND ASSURANCE

At the jobsite, techniques are needed to ensure that the mix delivered meets the design temperature of –5°C. The freezing point measurement, described earlier as part of the initial screening tests, was found to be a valuable quality control tool. In the lab, the relationship between the total percent solids and the resulting freezing point could be varied and plotted for use as a quick check in the field on the water content of the mix received at the jobsite. Should the mix not meet the design temperature of –5°C, due to an abundance of water, corrective action may be taken on site to adjust the quantity of admixtures (or increase the total percent solids content) and achieve the appropriate freezing point before releasing the concrete into the forms.

To do this, the freezing point measurement test from the lab was modified for field use and is conducted concurrent with other quality control testing done on site (slump and air content). To use this method rapidly in the field, smaller 50x102 mm test cylinders are filled with concrete, embedded with a temperature sensor, and placed in a cooler of dry ice. A datalogger records 1-second temperature readings while the cylinders cool. The data is processed to determine the freezing point.

Once the concrete has been placed and finished, the next step is to estimate the in-place strength of the structure. The maturity method, a non-destructive approach, uses the curing temperature and concrete age to estimate the in-place strength of the structure. The maturity method is capable of monitoring several locations in a structure, particularly ones that may be more susceptible to freezing. Prior to adopting the maturity method in the field, a lab study was conducted that determined the maturity method is appropriate for use with antifreeze concrete. Before the concrete is placed, several locations are instrumented with temperature sensors. It is best to select a range of locations that include both warm and cold curing conditions. The time-temperature method was found to give a conservative estimate of the concrete strength.

Sets of compressive strength cylinders are cast and cured at two different temperatures. One set cures at 25°C, while the other set cures in a picnic cooler located at the jobsite. Thermocouples are embedded in cylinders of fresh concrete to record temperatures. The age and strength values of the cylinders are used to create a strength-maturity relationship. The strength-maturity relationship and the temperatures from the structure are used to estimate the insitu strength gain of the structure.

FIELD DEMONSTRATION

A sidewalk was the site of the demonstration project in Concord, New Hampshire on February 14, 2003. Here, the antifreeze technology was transferred to the New Hampshire Department of Transportation. The antifreeze technology had been successfully validated at four other field sites prior to this. The Concord demonstration site by far, was the most challenging of all of the field sites. The 70 m sidewalk (Figure 7) was an experiment to test the durability of different commercially available surfaces to aid the visually impaired. The antifreeze concrete was placed at both the entrance and exit sections of the sidewalk.

The air temperatures in Figure 8 show that the overnight temperatures for the time period of February 13-15 reached as low as –30°C, with daytime temperatures only reaching a maximum of –10°C. These temperatures were some of the coldest reported in the past 25 years. The sidewalk was instrumented with temperature sensors at three depths at three separate locations (edge, center, and an additional internal location).

The ready mix plant was located 55 km away from the site and to prevent any problems with the mix in transit, the third dosing scheme was used, where all of the admixtures are added at the site. The truck left the plant carrying enough cement (392 kg/m^3 of Type II cement), fine and coarse aggregate, and water for 5.5m^3 of concrete with an anticipated w/c of 0.25. Given the cold temperatures, there was a concern that the mix might freeze on the way to the site. No significant changes were required for operations with antifreeze technology, which makes it conducive for use with standard operating procedures. However, it is recommended that agencies conduct testing on their own to become familiar with antifreeze mixes. Once at the site, the admixtures were added and thoroughly mixed. Initially, the mix was very stiff (25 mm) and additional water was slowly added to raise the slump to 100mm. The freezing point of the mix was estimated to be –6.5°C. The concrete was placed, consolidated, screeded, and immediately finished with both hand and magnesium bull floats. Antifreeze concrete may be finished without delay since it does not exhibit bleeding. Approximately 1½ hours after placement, once the surface had set, the concrete was covered with a sheet of plastic and a 25-mm thermal blanket to retain moisture. Overnight temperatures following the pour reached –25°C.

Compressive strength cylinders were cast and cured at room temperature at the NHDOT lab, along with two instrumented dummy cylinders to measure temperature. The temperatures and the compressive strength, were used to estimate the in-place strength at three locations from warmest to coldest (Figure 9). The warmest location was the center, and the coldest was along the outside edge. The target strength of 23 MPa was reached by the warmest location after 4½ days of curing, while the coldest location required about 7½ days to reach the target strength. The forms and thermal blanket were left on for a total of ten days and then removed so that construction activities could continue.

CONCLUSIONS

The development of "*Off-the-Shelf*" antifreeze admixtures for subfreezing concrete operations is an effective technology. This project met its goals of producing several antifreeze formulations that are capable of protecting fresh concrete down to an internal temperature of –5°C using commercially available chemical admixtures. These mixes develop early age strength when at low curing temperatures. Several large-scale field tests successfully demonstrated their performance. The antifreeze mixes were workable and capable of entraining air. This initial phase of the project applied antifreeze technology to Type I/II portland cement. Future research is needed to develop antifreeze technology for other types of cements, to include blended cements that contain slag or fly ash.

ACKNOWDLEGEMENT

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REFERENCES

ASTM (1999) C 33-99, Standard specification for concrete aggregates. In *Annual Book of ASTM Standards*, vol. 4.02. West Conshohocken, PA: American Society for Testing and Materials.

ASTM (2000) C 150-00, Standard specification for portland cement. In *Annual Book of ASTM Standards*, vol. 4.01. West Conshohocken, PA: American Society for Testing and Materials.

ASTM (1994) C 173-94ae1, Standard test method for air content of freshly mixed concrete by the volumetric method. In *Annual Book of ASTM Standards*, vol. 4.02. West Conshohocken, PA: American Society for Testing and Materials.

ASTM (2000) C 260-01, Standard specification for air-entraining admixtures for concrete. In *Annual Book of ASTM Standards*, vol. 4.02. West Conshohocken, PA: American Society for Testing and Materials.

ASTM (1999) C 494-99ae1, Standard specification for chemical admixtures for concrete. In *Annual Book of ASTM Standards*, vol. 4.02. West Conshohocken, PA: American Society for Testing and Materials.

ACI (1991) *Standard Practice for Selecting Proportions for Normal, Heavyweight and Mass Concrete*. ACI 211.1-91. Detroit, Michigan: American Concrete Institute.

ACI (1988) *Cold Weather Concreting*. ACI 306R-88. Detroit, Michigan: American Concrete Institute.

Korhonen, Charles J., Peter M. Semen and Lynette A. Barna (2004) Extending the Season for Concrete Construction and Repair, Phase I – Establishing the Technology. USAERDC Cold Regions Research and Engineering Laboratory. Technical Report, TR-04-2.

TABLE 1 General Types of Chemical Admixtures Used In Developing Antifreeze Concrete Formulations

TABLE 2 Chemical Admixtures and Dosages Used In Developing An Antifreeze Concrete Formulation

TABLE 3 Laboratory Air Content Measurements From Freshly Mixed Control and Antifreeze Concrete at 5 and 55 Minutes

FIGURE 1 An example of conventional cold weather concrete practice.

FIGURE 2 Map of the United States showing the potential extension of the concrete season with antifreeze concrete technology.

FIGURE 3 Comparison of control mix with antifreeze mixes for each dosing method.

FIGURE 4 A typical freezing point curve for an antifreeze mix.

FIGURE 5 Results of compressive strength testing of cylinders using admixtures from Company A, cured at –4°C reported as a percentage of the 28-day control strength cured at 25°C and compared to recommended values cured at 4.4°C based on ACI 306-R88 (1988).

FIGURE 6 Results of compressive strength testing of cylinders using admixtures from Company B, cured at –4°C reported as a percentage of the 28-day control strength cured at 25°C and compared to recommended values cured at 4.4°C based on ACI 306-R88 (1988).

FIGURE 7 Photograph of the Concord, New Hampshire field site.

FIGURE 8 Temperature data for Concord, New Hampshire before and after the pour.

FIGURE 9 Estimated strength gain at three locations, warmest to coldest, in the sidewalk at the Concord, New Hampshire demonstration site.

TABLE 1 General Types of Chemical Admixtures Used In Developing Antifreeze Concrete Formulations

Specification Standard		Description
ASTM C 494	Type A	Water-reducing
	Type B	Retarding
	Type C	Accelerating
	Type D	Water-reducing and retarding
	Type E	Water reducing and accelerating
	Type F	High-range water-reducing
	Type G	High-range water-reducing and retarding
ASTM C 260		Air-entraining
(None)		Corrosion-inhibiting
(None)		Shrinkage-reducing

TABLE 2 Chemical Admixtures and Dosages Used In Developing An Antifreeze Concrete Formulation

Product Type (dosage level)	Admixture Dosage	
	Antifreeze	**Control**
Type A - Water Reducing [mL/100 kg]	780	130
Type F - High-Range Water Reducing [mL/100 kg]	195	–
Corrosion Inhibitor [L/m^3]	30	–
Type E - Accelerating [mL/100 kg]	6520	–
Air Entraining [mL/100 kg]	90	25
w/c ratio	0.442	0.435
Freezing point (°C)	-5.5	-1.0
% Total Solids (by wt of water)	16.03	0.08

TABLE 3 Laboratory Air Content Measurements From Freshly Mixed Control and Antifreeze Concrete at 5 and 55 Minutes

	Mix	Air Content Measurements (%) 5-minute	55-minute
	Control	7.0	5¼
Admixture Company A	**Mix 1**	4.0	7¾
	Mix 2	4.0	~ 9½
	Mix 3	3.0	~ 11¾
	Mix 4	5¼	8.0
Admixture Company B	**Mix A**	4¼	4¼
	Mix B	4½	4.0
	Mix C	2.0	2¾
	Mix D	~ 11.0	5½

FIGURE 1 An example of conventional cold weather concrete practice.

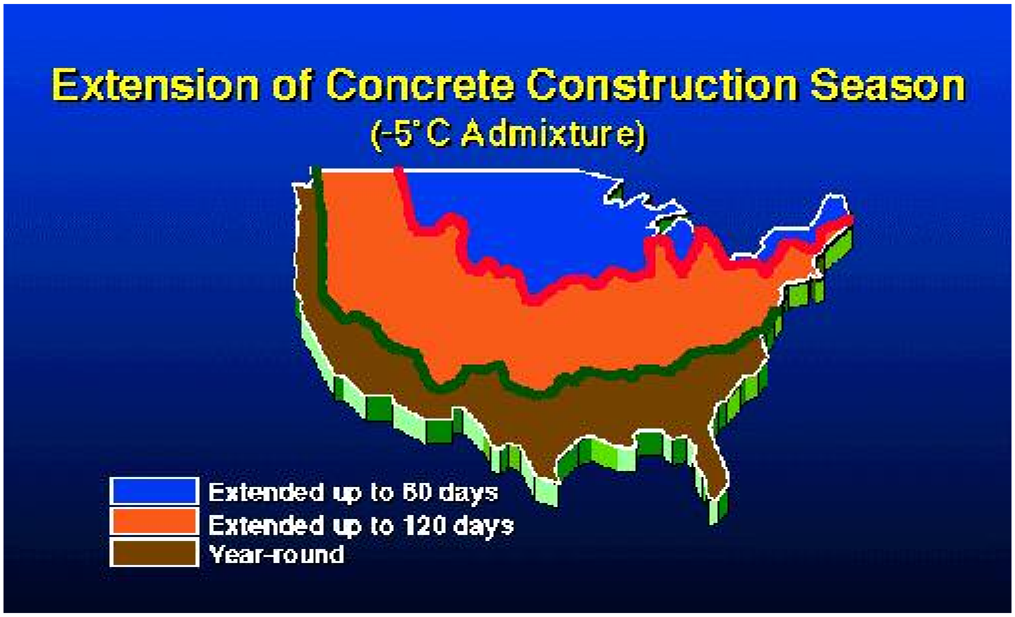


FIGURE 2 Map of the United States showing the potential extension of the concrete season with antifreeze concrete technology.

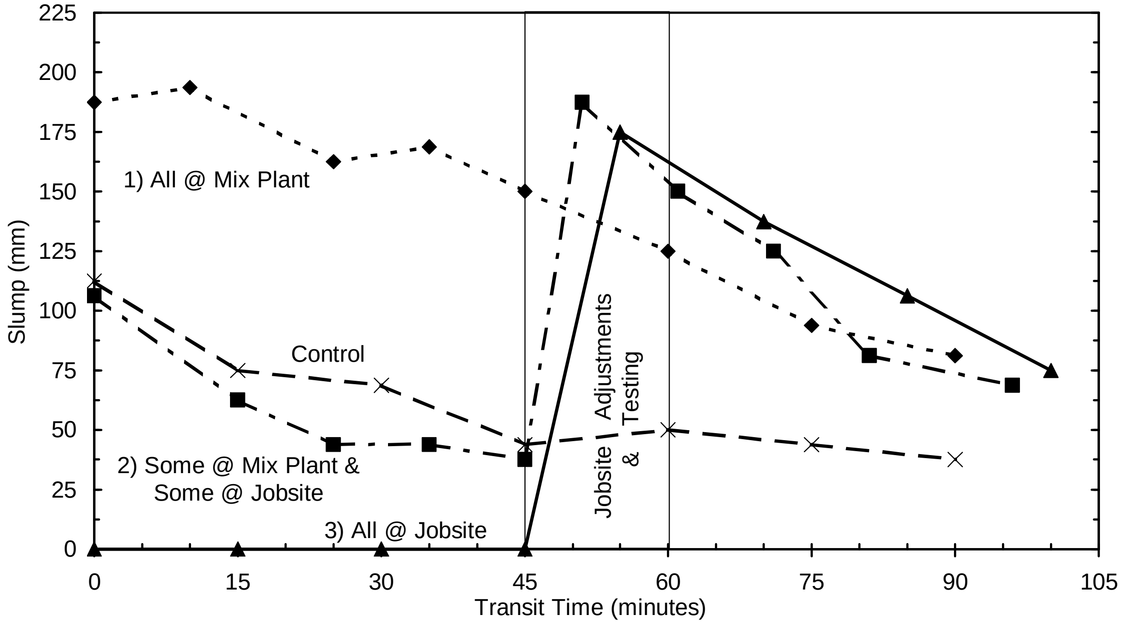
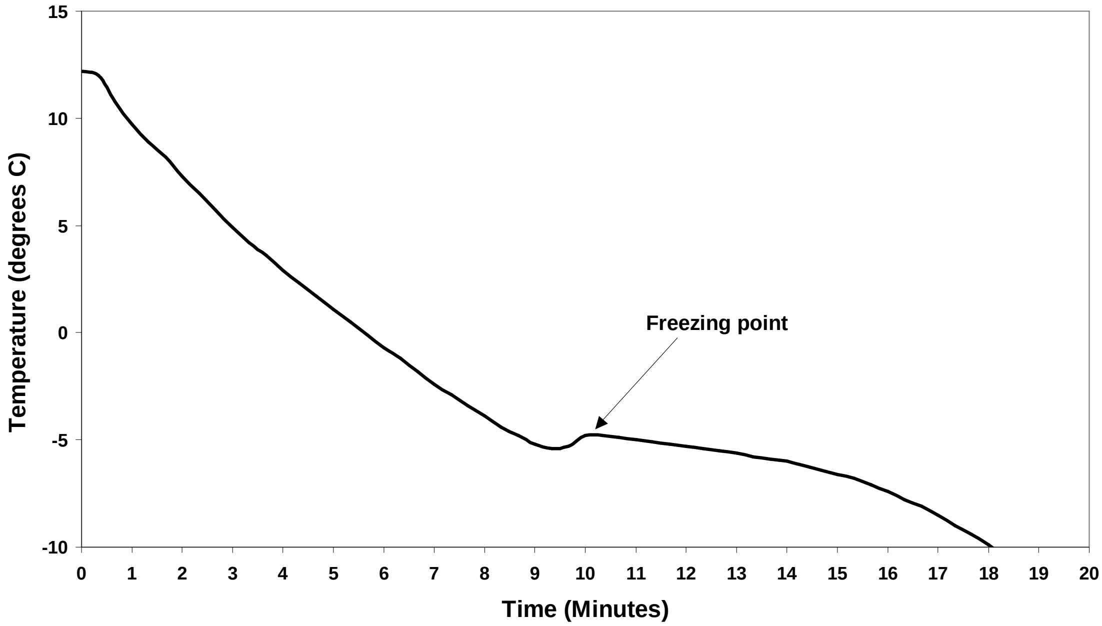


FIGURE 3 Comparison of control mix with antifreeze mixes for each dosing method.



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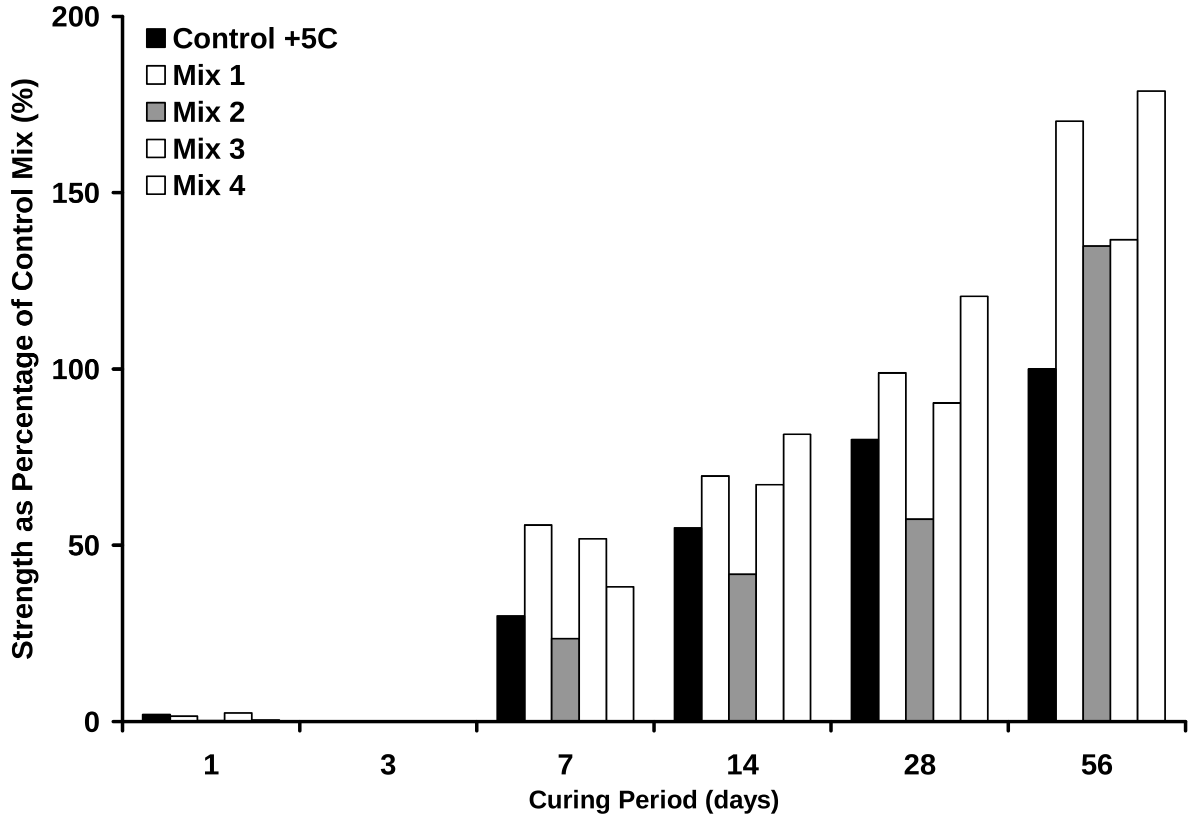

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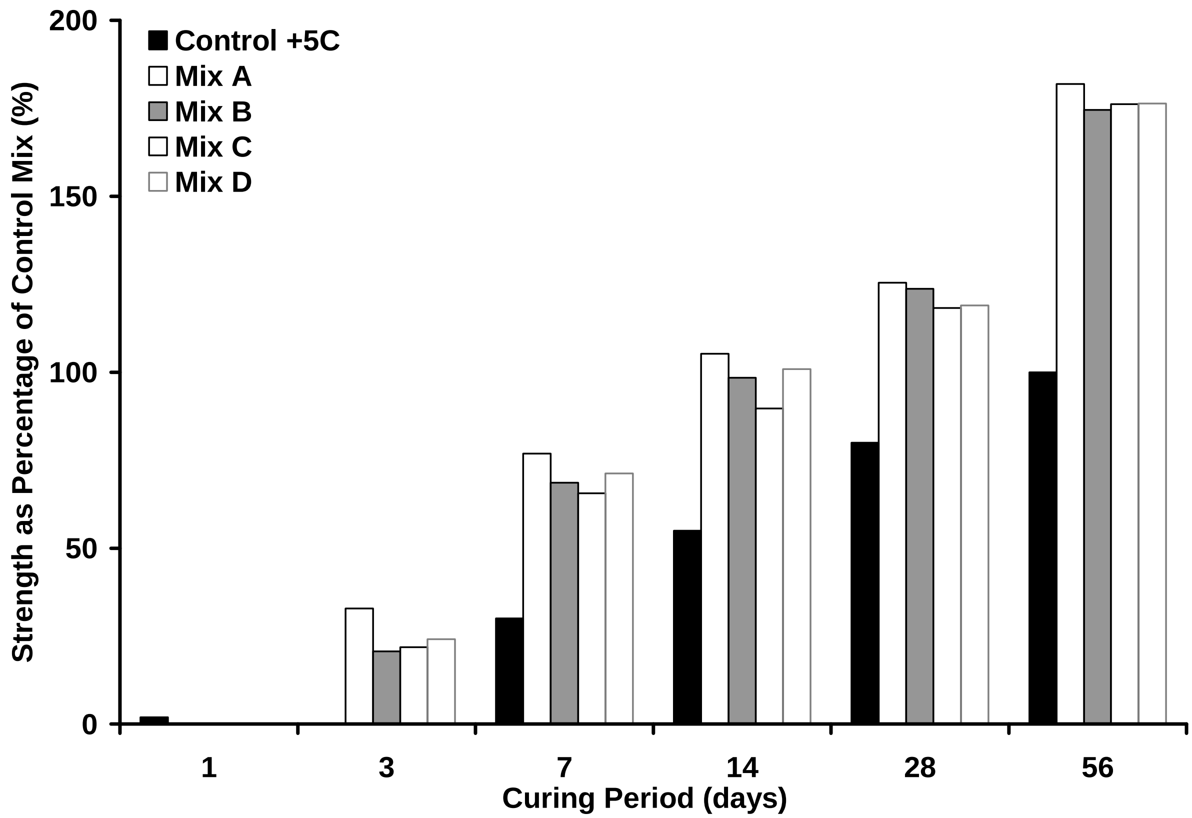
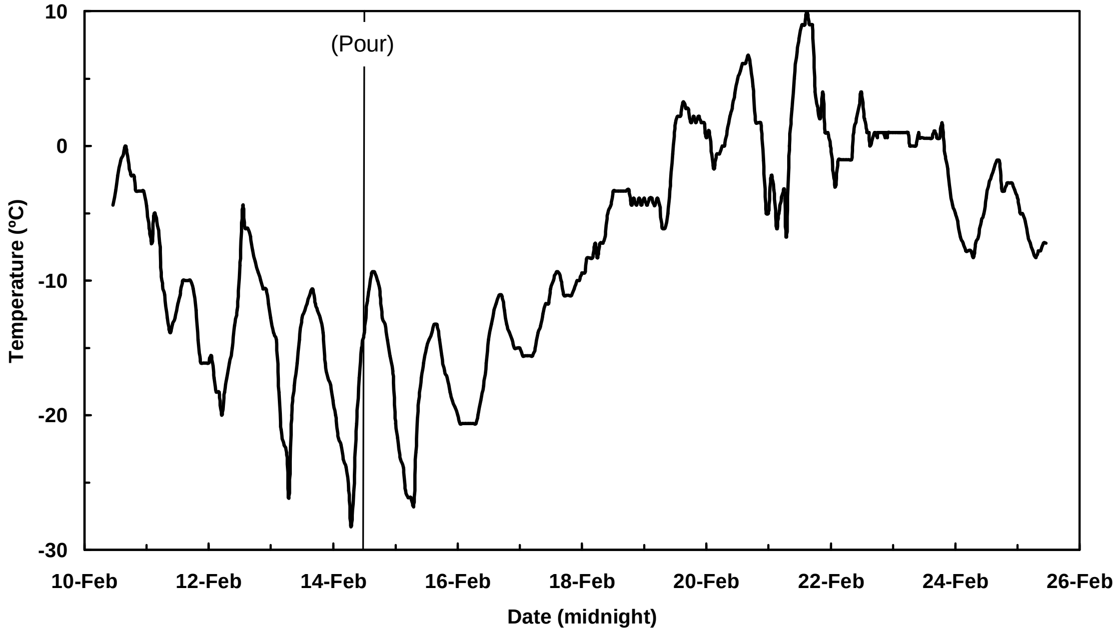


FIGURE 6 Results of compressive strength testing of cylinders using admixtures from Company B, cured at –4°C reported as a percentage of the 28-day control strength cured at 25°C and compared to recommended values cured at 4.4°C based on ACI 306-R88 (1988).

FIGURE 7 Photograph of the Concord, New Hampshire field site.



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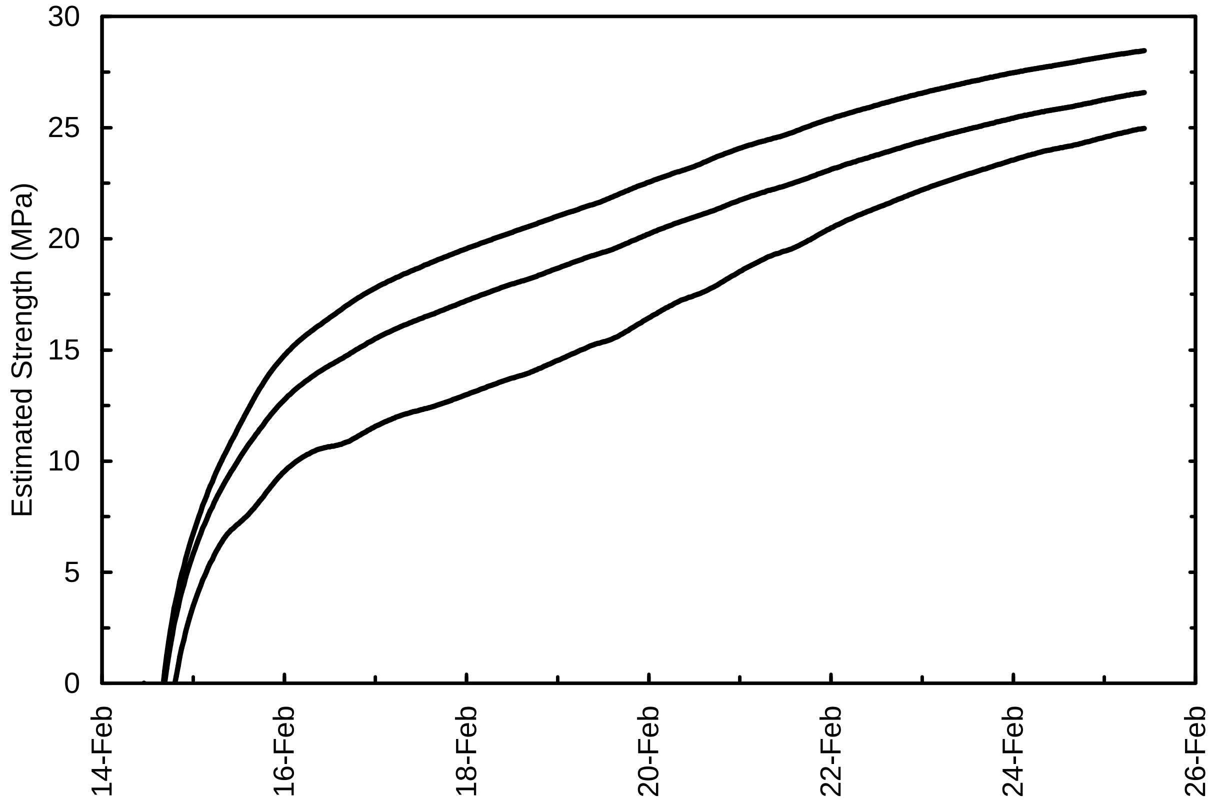

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